Stable massive particles at the LHC: novel interpretations and future prospects

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Two distinct parts

1) **Interpretation** of current limits in long-lived **squarks** in specific SUSY models
   - Couplings in RPV SUSY

2) **Sensitivities** of the LHC experiments to **highly ionizing particles**
   - Acceptances for direct detection of high masses and charges
   - Trapped magnetic monopoles

PART 1: interpretations of metastable squark limits in the RPV SUSY framework

RPV SUSY

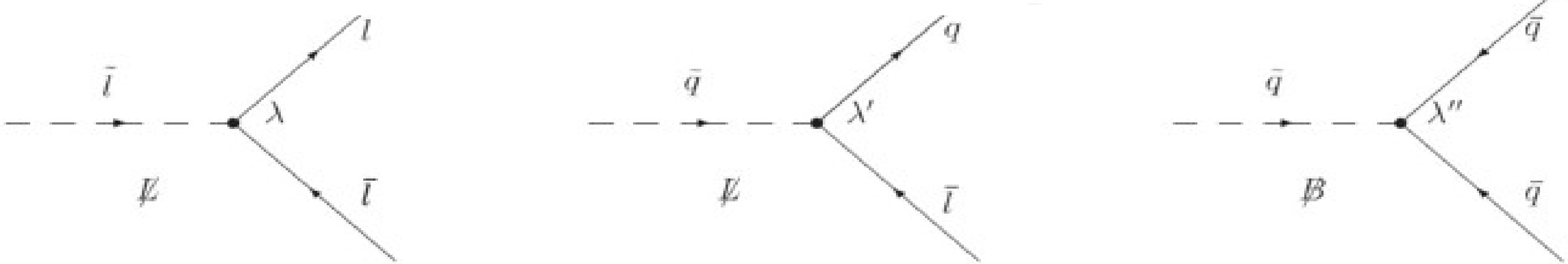
- What is it good for ?
  - Hierarchy problem
  - Unification of couplings
  - Violates lepton flavour number - neutrino oscillations
- What can't it do ?
  - Dark matter
    - LSP can be any sparticle

- Perhaps anyway over-ambitious to expect our theory to solve lots of problems at the same time.

RPV SUSY – trilinear couplings

General SUSY Lagrangian contains L and B violating terms

$$\mathbf{W}_{\not{R}_P} = \epsilon_{ab}\left[\frac{1}{2}\underbrace{\lambda_{ijk}L_i^a L_j^b \bar{E}_k}_{\text{violates } L} + \underbrace{\lambda'_{ijk}L_i^a Q_j^{bx}\bar{D}_{kx}}_{\text{violates } L}\right] + \frac{1}{2}\epsilon_{xyz}\underbrace{\lambda''_{ijk}\bar{U}_i^x \bar{D}_j^y \bar{D}_k^z}_{\text{violates } B} - \epsilon_{ab}\underbrace{\kappa^i L_i^a H_u^b}_{\text{violates } L}$$



$$\Gamma(\tilde{d}_{1k} \to \nu_i d_j) = \frac{m_{\tilde{d}_{1k}}}{16\pi}\cos^2\theta_{\tilde{d}_k}|\lambda'_{ijk}|^2 \qquad \Gamma(\tilde{q}_1 \to qq) = \frac{m_{\tilde{q}_1}}{2\pi}\cos^2\theta_{\tilde{q}}\,|\lambda''_{ijk}|^2$$

λ' and λ'' small enough → squark R-hadron

RPV limits

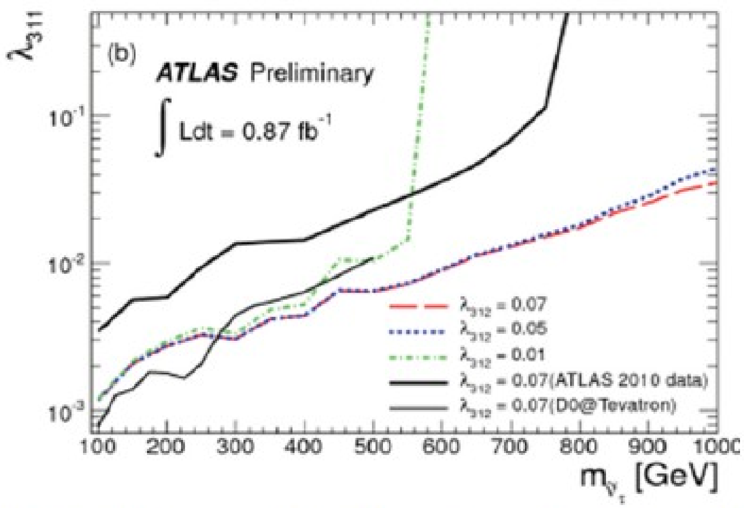
(H. Dreiner, hep-ph/9708435)

ijk	λ_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ''_{ijk}
121	$0.05^{a\dagger}$	111	0.001^{d}	211	0.09^{h}	311	0.16^{k}	112	$10^{-6,\ell}$
122	$0.05^{a\dagger}$	112	$0.02^{a\dagger}$	212	0.09^{h}	312	0.16^{k}	113	$10^{-5,m}$
123	$0.05^{a\dagger}$	113	$0.02^{a\dagger}$	213	0.09^{h}	313	0.16^{k}	123	1.25^{**}
131	0.06^{b}	121	$0.035^{e\dagger}$	221	0.18^{i}	321	0.20^{f*}	212	1.25^{**}
132	0.06^{b}	122	0.06^{c}	222	0.18^{i}	322	0.20^{f*}	213	1.25^{**}
133	0.004^{c}	123	0.20^{f*}	223	0.18^{i}	323	0.20^{f*}	223	1.25^{**}
231	0.06^{b}	131	$0.035^{e\dagger}$	231	$0.22^{j\dagger}$	331	0.26^{g}	312	0.43^{g}
232	0.06^{b}	132	0.33^{g}	232	0.39^{g}	332	0.26^{g}	313	0.43^{g}
233	0.06^{b}	133	0.002^{c}	233	0.39^{g}	333	0.26^{g}	323	0.43^{g}

Table 1: Strictest bounds on $R\!\!\!/_p$ Yukawa couplings for $\tilde{m} = 100\,GeV$. The physical processes from which they are obtained are summarized in the main text.

Indirect inferred limits from low energy processes and basic arguments.

(see arXiv:1103.5559)



Direct collider searches

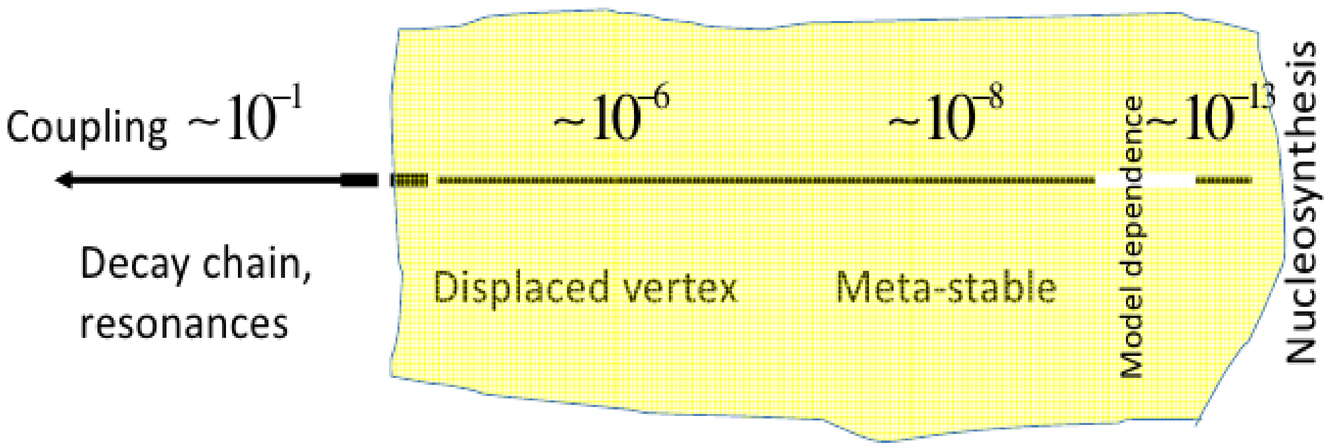
45 independent couplings : 2^{45}–1 non-vanishing combinations

Simplification assumption: assume one dominant coupling

Constraining RPV couplings

We consider searches with non-decaying particles

- Typical signature: high p_T, high dE/dx, delayed
- High luminosity
- Complementary to displaced vertex signatures
- Not reliant on assumptions of decay products
  → offers a full ”sweep” over topologies



Exclude couplings over many orders of magnitude

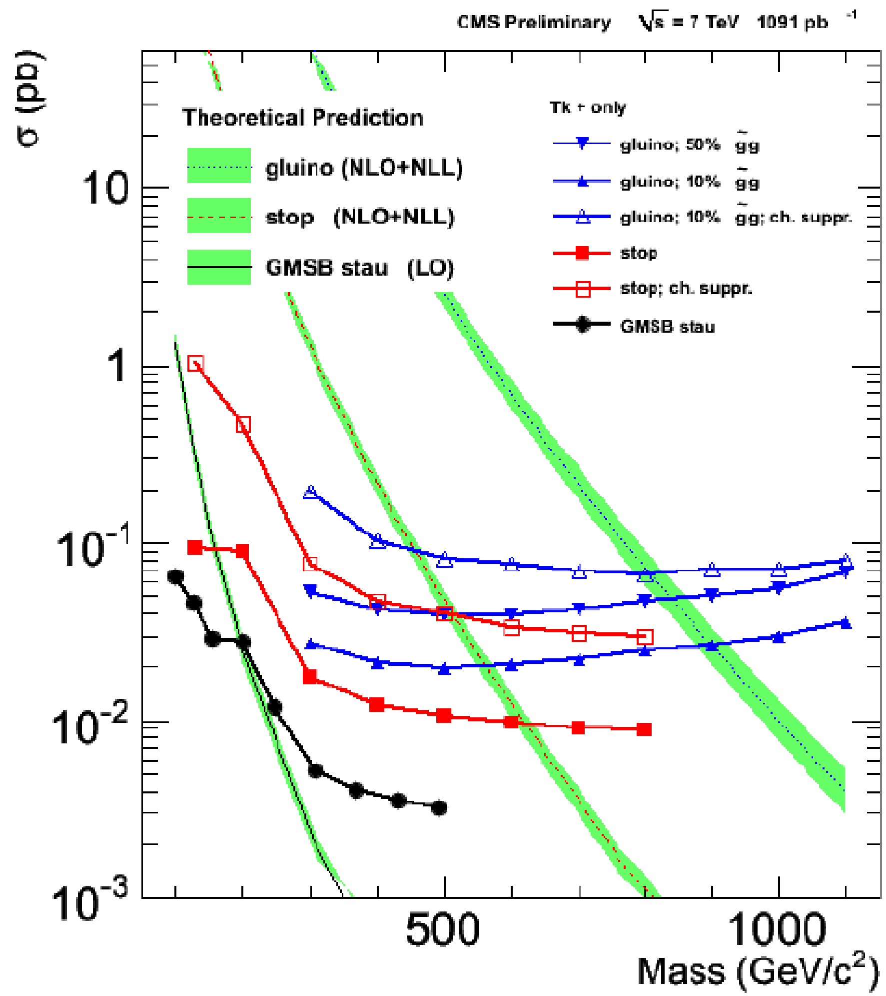
Non-decaying particles – current limits

- Both ATLAS and CMS have set limits beyond the Tevatron for metastable squarks and gluinos

- Best current limits: CMS preliminary

  (CMS PAS EXO-11-022)

  → we use the stop limits with track-only selection in our calculations



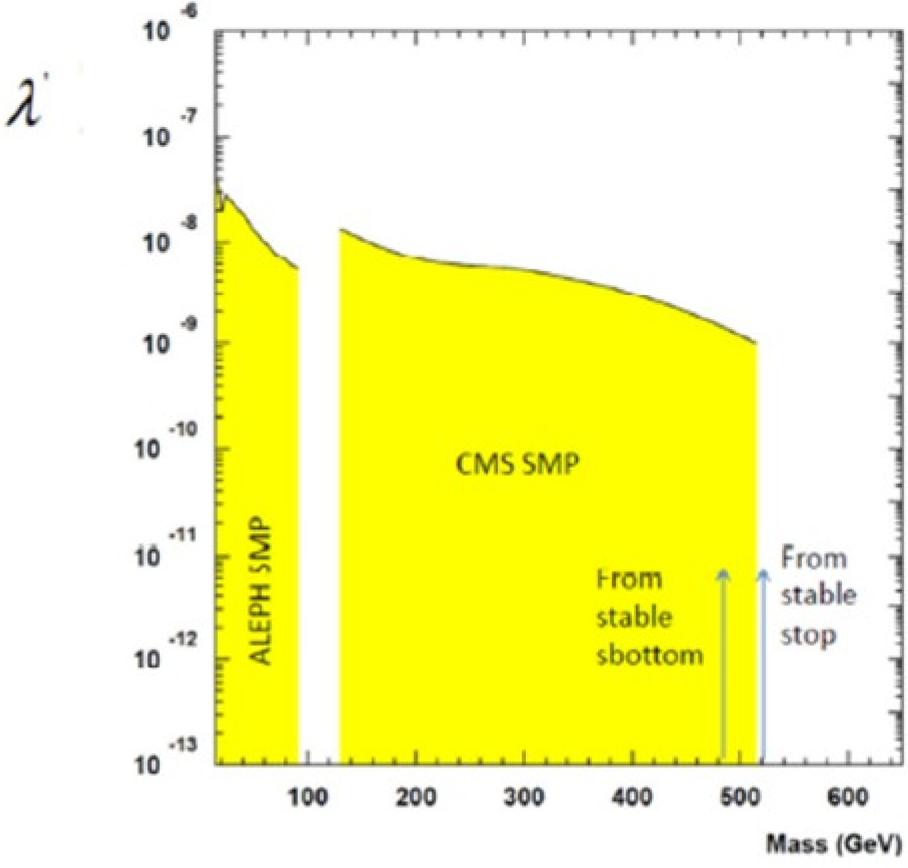
Strategy to extract limits on couplings

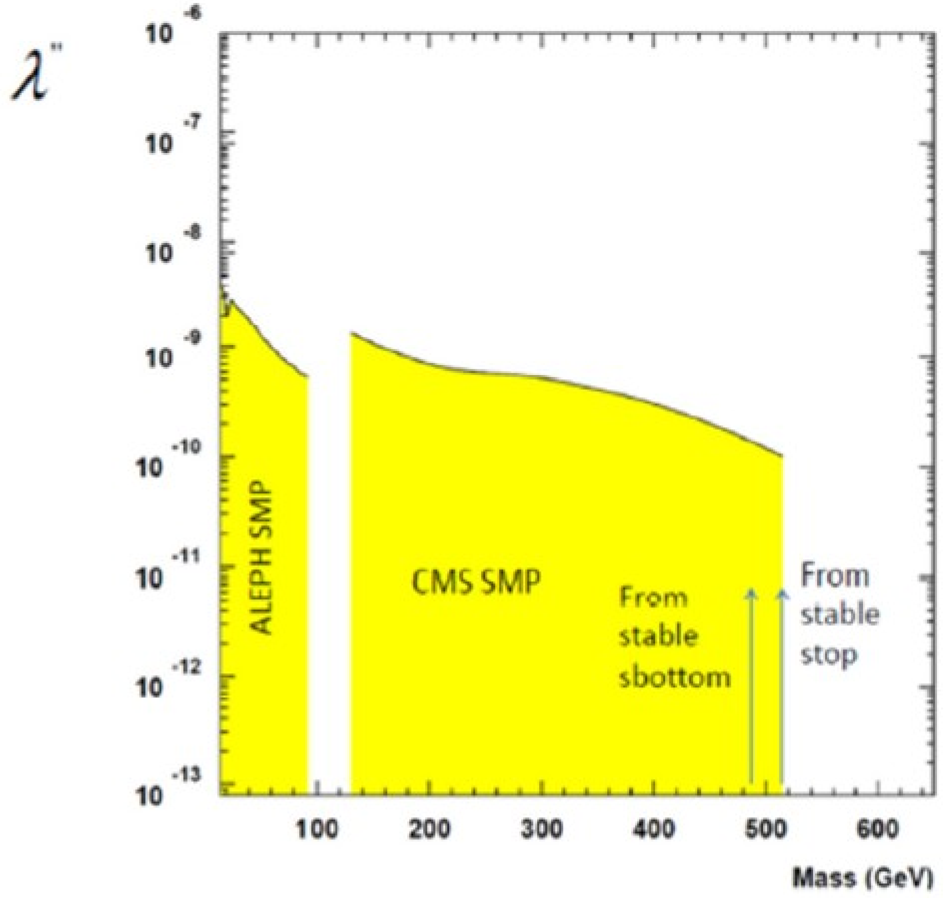
Search was designed for long lifetime
$\rightarrow$ extrapolate to short lifetimes

- Conservative assumption for acceptance loss calculation:
  both particles required not to decay in detector
  (exponential decay + time dilatation)
- Pythia to model kinematics of production
- CMS preliminary mass limits
- NLO+NLL cross section calculations
- Reduce predicted cross section with lifetime weighting

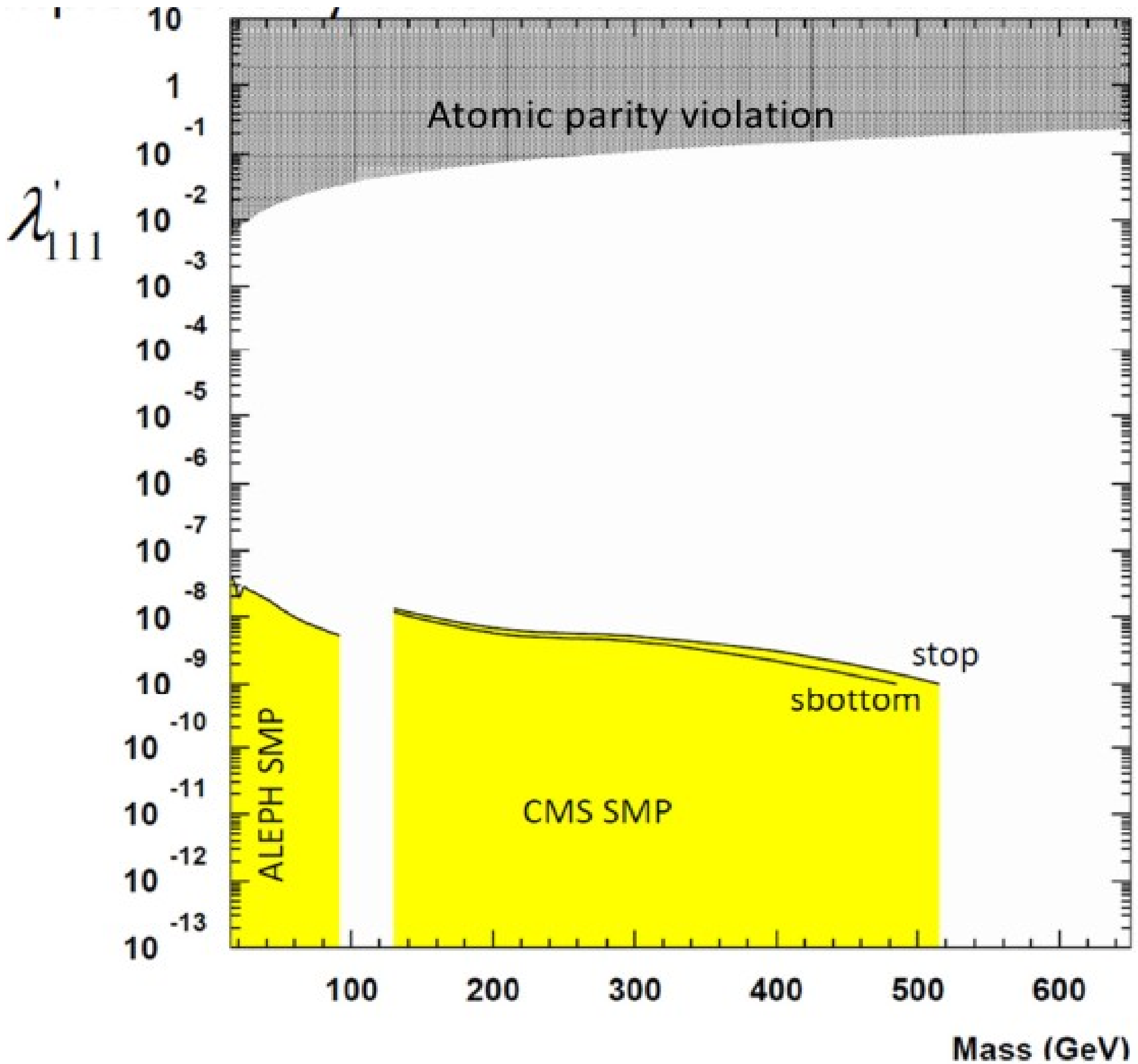
Generic exclusion of λ' and λ''

Estimate equivalent mass limit for sbottoms with correction for reduced rate of charged hadrons after hadronisation.





Complementary constraints for an individual coupling



Squark couplings – conclusions

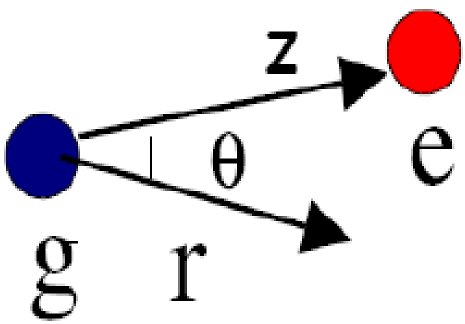
The CMS experimental constraints on stable squarks were used to constrain squark with shorter lifetimes. Specifically, we extracted:

- Limits on stop couplings to SM particles in the range ~100 < Mass < ~500 GeV
- RPV SUSY interpretation: generic exclusion of coupling strengths over many orders of magnitude

PART 2: future prospects for highly-ionizing particle searches

Highly ionizing particles (HIPs)

- **Magnetic Monopoles**
  - Dirac's argument (1931) – angular momentum of field of electron-monopole system:



$$L=\int r\times E\times B\,dr\,d\theta\,d\phi$$

$$=\frac{\mu_0 e g}{4\pi}\hat{z}\Rightarrow e=\frac{nh}{g\mu_0}\qquad g_D=\frac{h}{e\mu_0}$$

Elementary charge?

electron: $g=g_D=68.5e$

down quark: $g=3g_D$

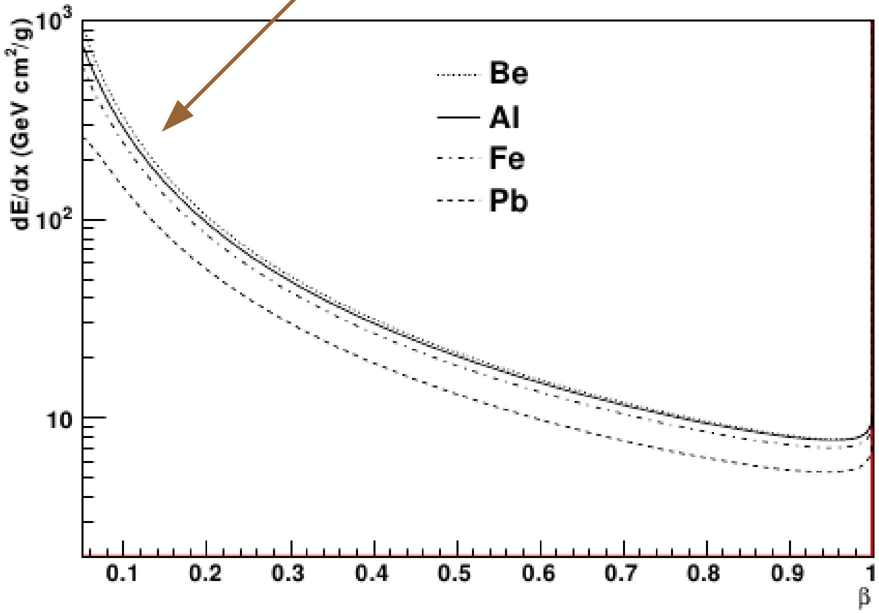
other?

  - "explain" charge quantization
  - Symmetrize Maxwell's equations
  - Ingredient in Grand Unification Theories
- **Highly-charged particles** $|z| >> e$ (Qballs, micro black hole remnants, ...)

HIPs: ionization energy loss

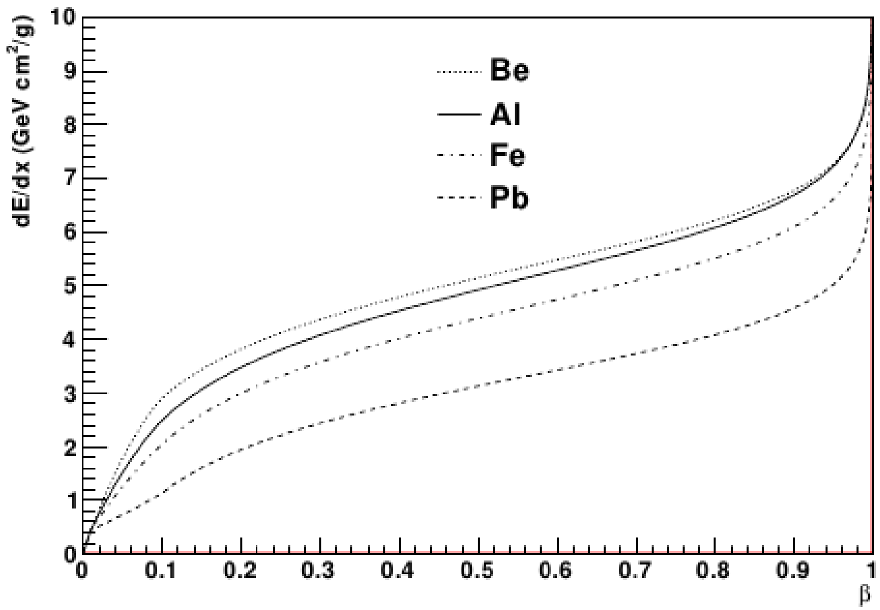
Electric

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$



Magnetic

$$-\frac{dE}{dx} = Kg^2\frac{Z}{A}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I_m} + \frac{K(|g|)}{2} - \frac{1}{2} - \frac{\delta_m(\beta\gamma)}{2} - B(|g|)\right]$$

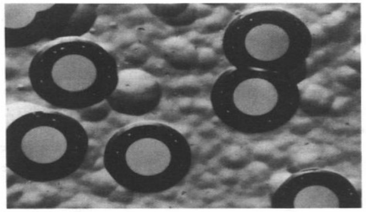


Monopole with $|g| = g_D$ equivalent to $|z| = 68.5e$ for $\beta \sim 1$,

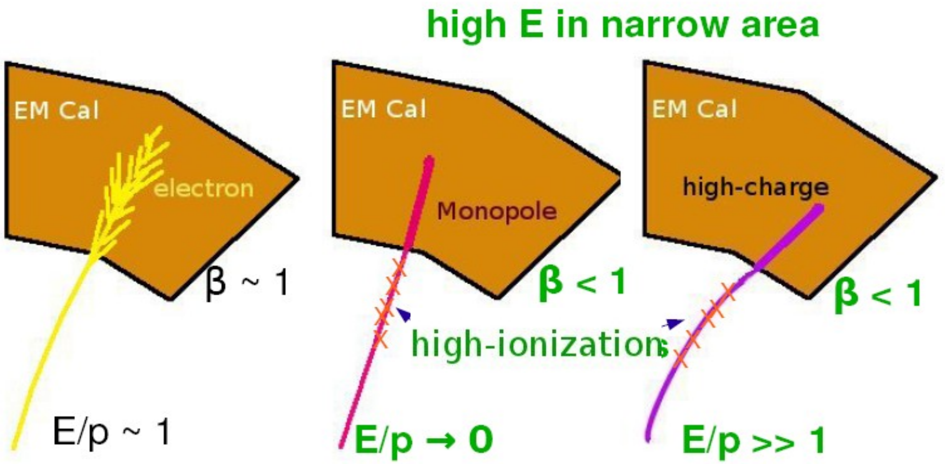
but low-speed behavior is very different

Direct HIP detection techniques at colliders

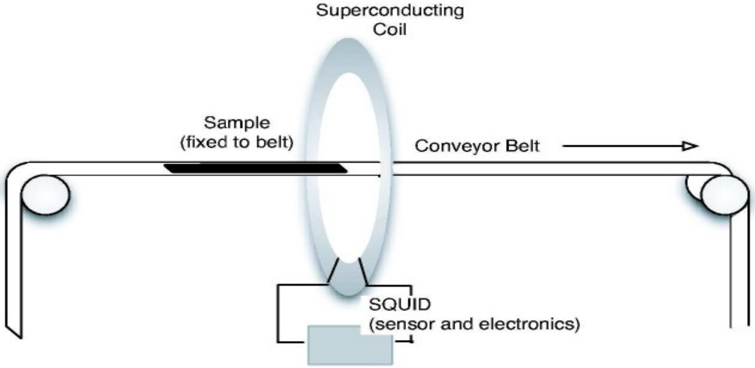
- **Track-etch technique**
  - **LEP, Tevatron**
  - **MoEDAL** experiment to be deployed near LHCb



- **Multipurpose detector**
  - **OPAL, CDF**
  - **ATLAS, CMS, ALICE**



- **SQUID technique**
  - **HERA, Tevatron**
  - **LHC**

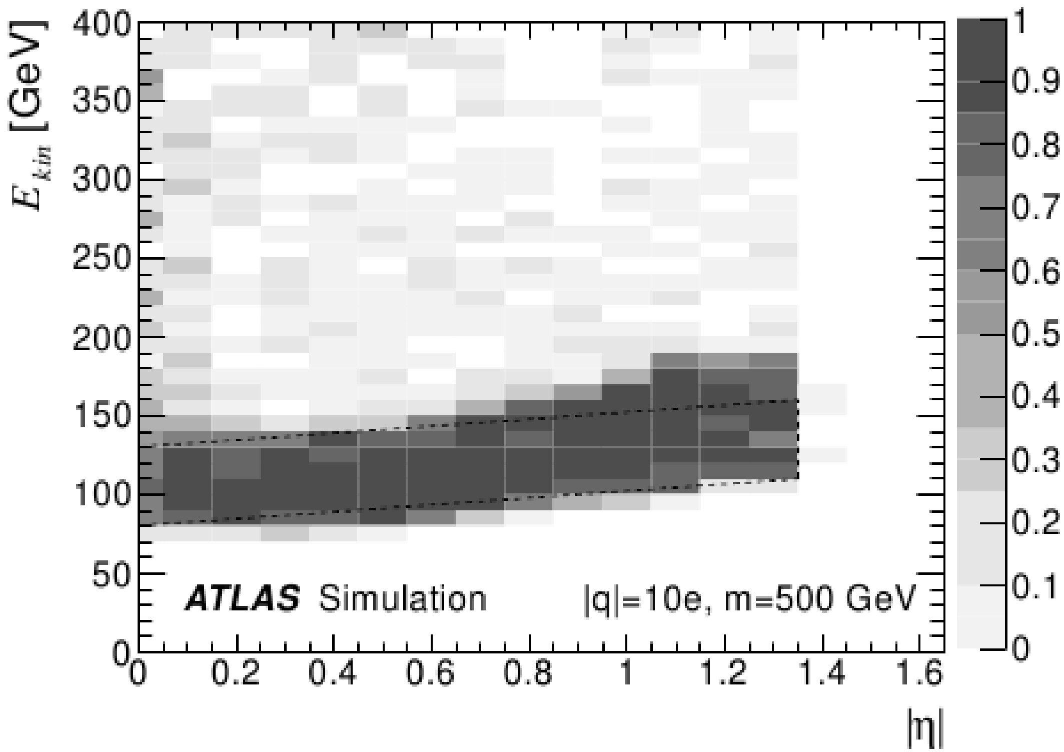


ATLAS HIP search with first data

arXiv:1102.0459v3 [hep-ex]

Signature: electron-like object with high ionization and narrow cluster

- → Exclusion limits for electrically charged HIPs $6e \leq |z| \leq 17e$ and mass up to 1000 GeV



Is the search also sensitive to magnetic charges?

- $|g| < g_D/2$: too low energy in calorimeter
- $|g| \geq g_D/2$: delta electrons spoil the tracking

Answer is: no

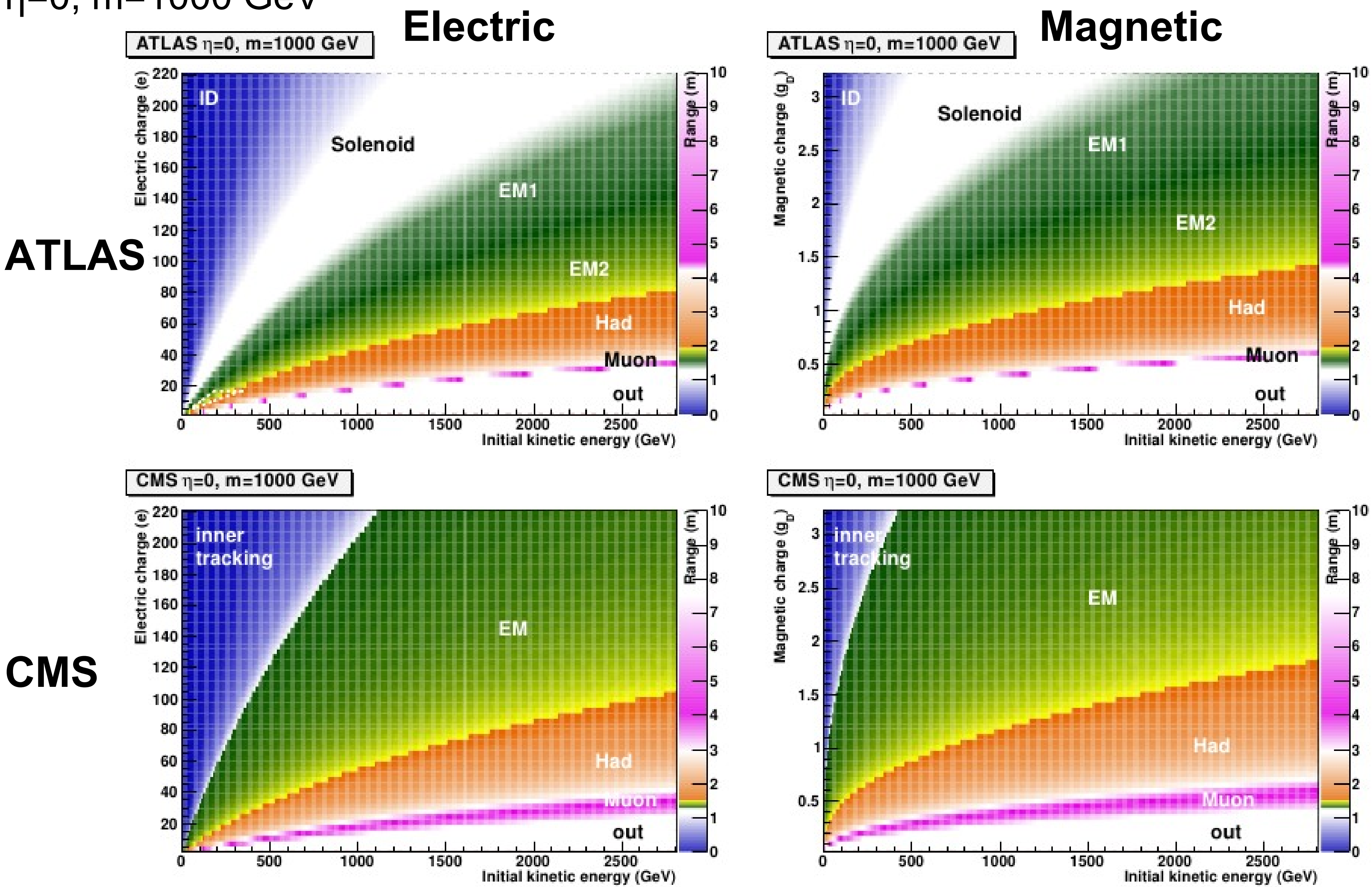
Where do the HIPs stop?

Determine for each mass and charge knowing detector composition and initial direction and energy

JINST 3 S08003 (ATLAS)
JINST 3 S08004 (CMS)
JINST 3 S08002 (ALICE)

Where do the HIPs stop – ATLAS and CMS

η=0, m=1000 GeV

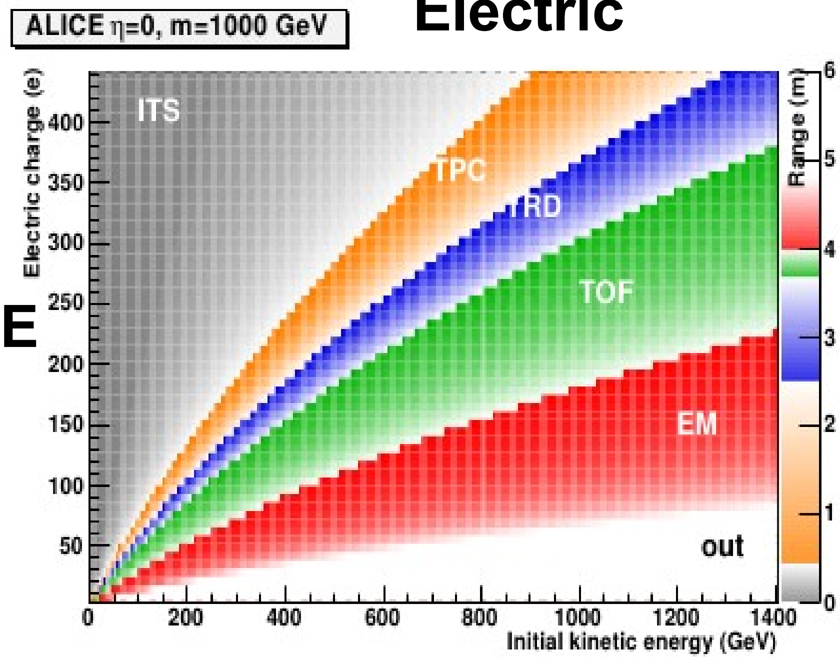


Where do the HIPs stop – ALICE

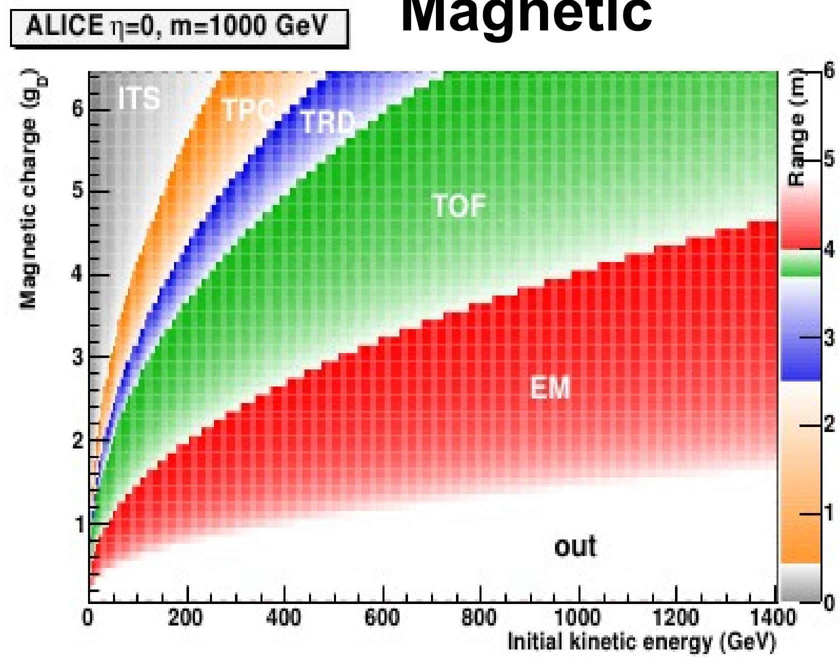
η=0, m=1000 GeV

Electric

ALICE



Magnetic



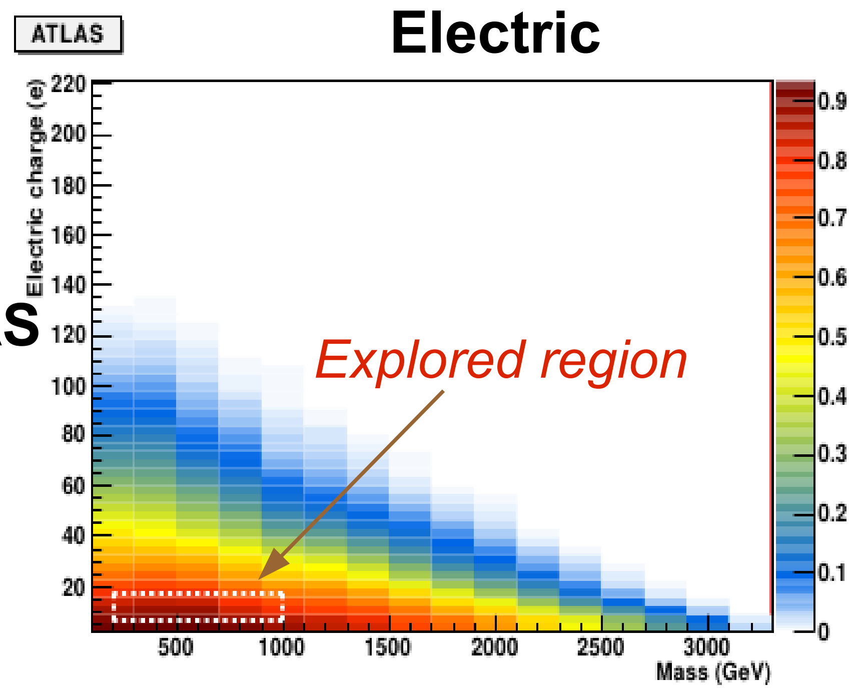
- ATLAS solenoid magnet prevents HIPs of low energy and high charge to reach EM calorimeter
- ALICE has much lower material budget → sensitive to much lower energies and higher charges

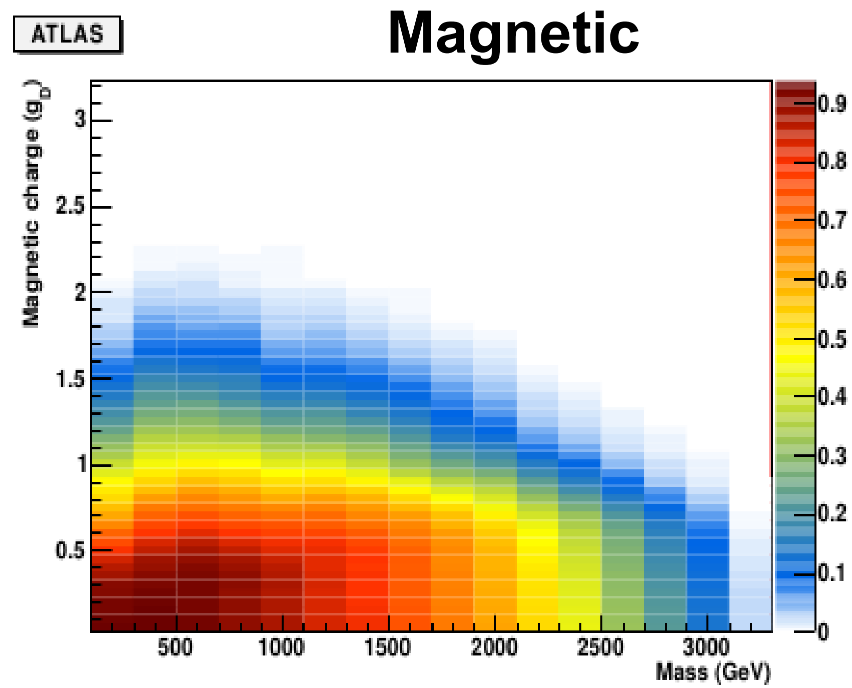
HIP acceptances – definitions

- **Acceptances** are defined as functions of particle mass and charge for a given production model (e.g. Drell-Yan)
- For detection at general-purpose experiments:
  - fraction of events with at least one HIP entering a region of the detector where it has a high probability to induce a level-1 trigger signal
    - ATLAS and CMS: energy deposition in EM calorimeter within the event's bunch crossing time window
    - ALICE: traverse the TPC
  - Detector efficiencies are not considered
- For detection of trapped monopoles with a SQUID experiment:
  - fraction of events with at least one HIP stopping inside the detector component to be analyzed (here ATLAS or CMS beam pipe)

HIP acceptances – ATLAS detector
Drell-Yan, 7 TeV *pp* collisions

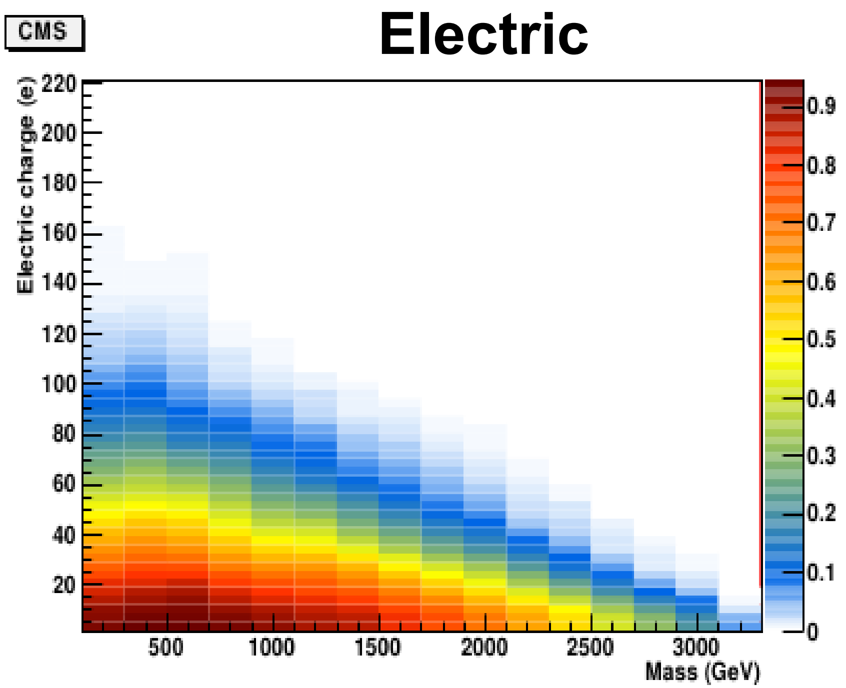
ATLAS

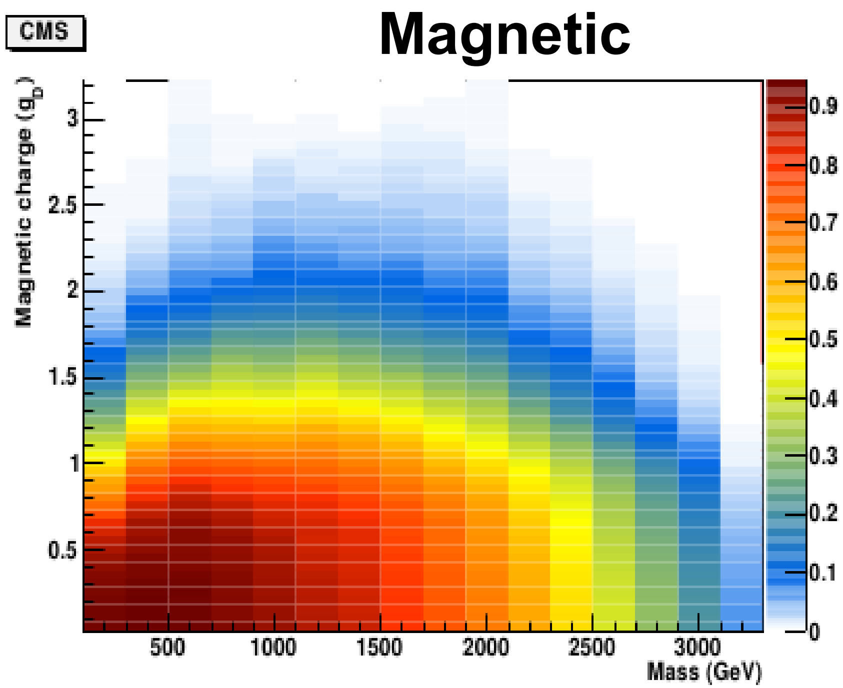




HIP acceptances – CMS detector Drell-Yan, 7 TeV *pp* collisions

CMS

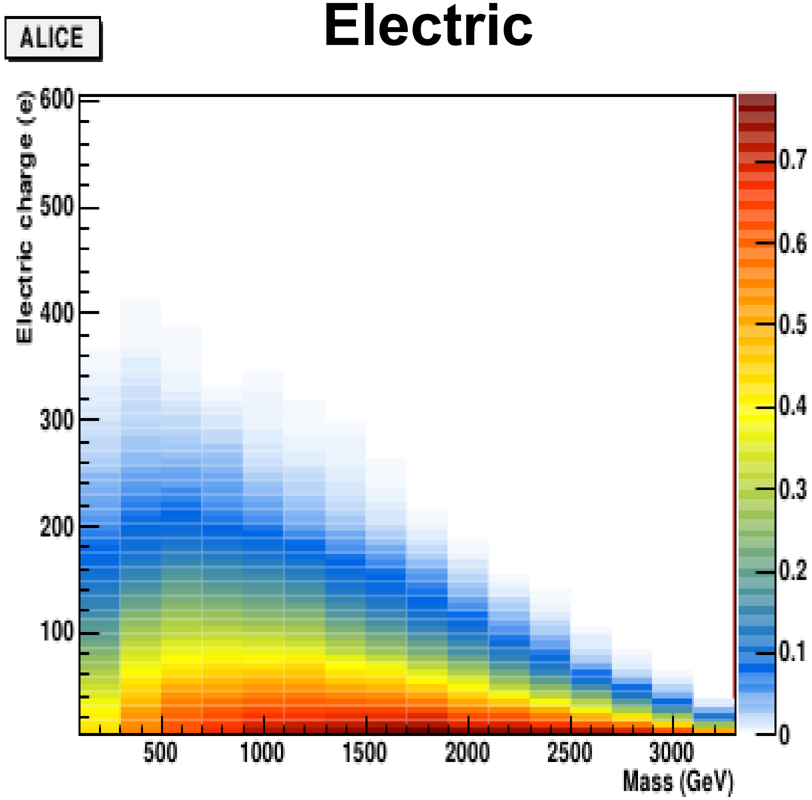




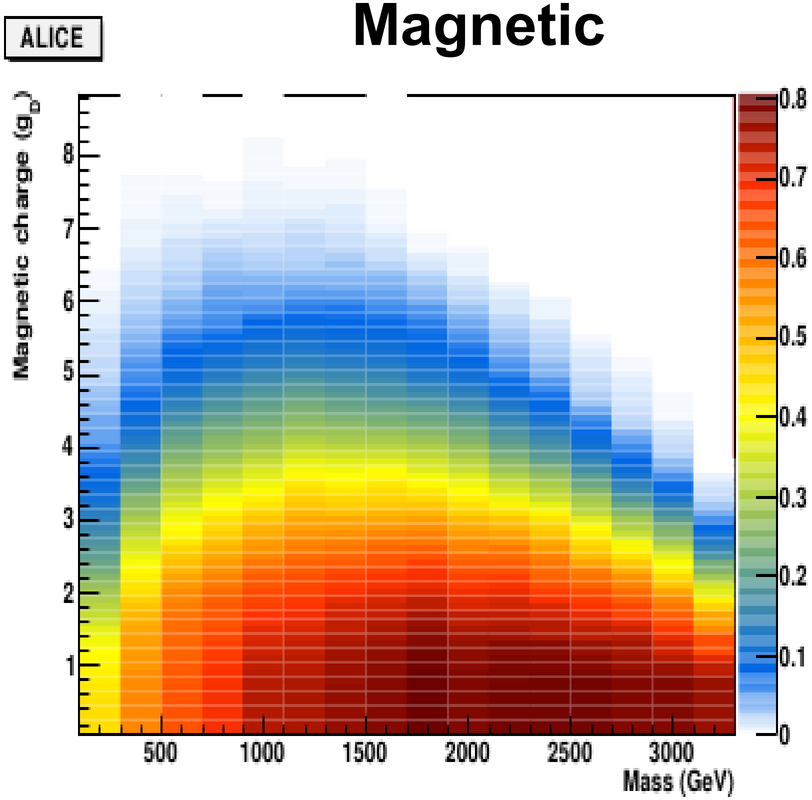
HIP acceptances – ALICE detector
Drell-Yan, 7 TeV *pp* collisions

ALICE

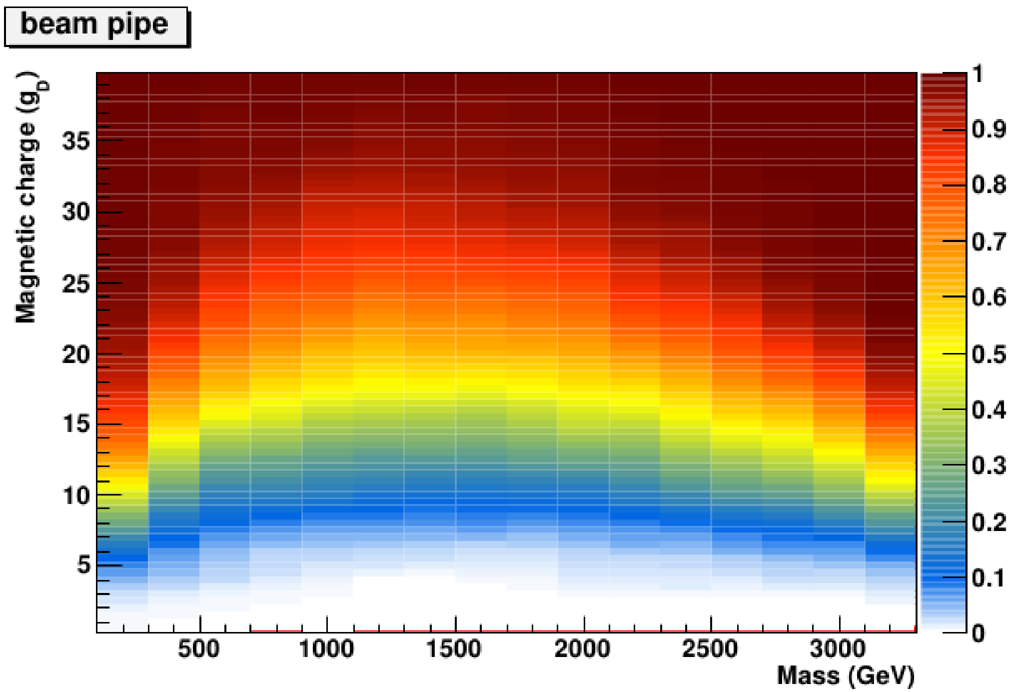
Electric



Magnetic



Monopole acceptance – SQUID technique, Drell-Yan, 7 TeV *pp* collisions



ATLAS/CMS beam pipe, to be replaced in 2013:

Beryllium cylinder

Inner radius 29 mm

Thickness 0.8 mm

Length ~4 m

Most sensitive to very high charges, complementary to other searches

HIP sensitivities – conclusions

- Large potential for HIP searches in the short term
  - Magnetic monopoles are still unconstrained at LHC energies!
  - This work provides reference for future HIP searches
- Complementary techniques can potentially cover wide ranges in charge and mass
  - Medium mass and charge ($|g| < 3g_D$), high luminosity
    - ✓ ATLAS and CMS
  - High mass and charge ($|g| < 8g_D$), low luminosity
    - ✓ ALICE and MoEDAL
  - Very high charge ($2g_D < |g| < 10000g_D$), high luminosity
    - ✓ SQUID with ATLAS and CMS beam pipes

Extra slides

Existing limits on RPV couplings

Source	Best Limits	Comment
Tevatron & HERA	$\lambda, \lambda', \lambda'' < 10^{-2}$	Mostly squark mass dependent
Low Energy experiments	$\lambda, \lambda', \lambda'' < 10^{-2}\ m_l/100\text{GeV}$	Proportional to sfermion mass
Proton decay	$\lambda'\lambda'' < 10^{-11}$	No limit on single couplings!
Cosmology	$\lambda, \lambda', \lambda'' < 5\ 10^{-7}$	Model dependent!

45 =

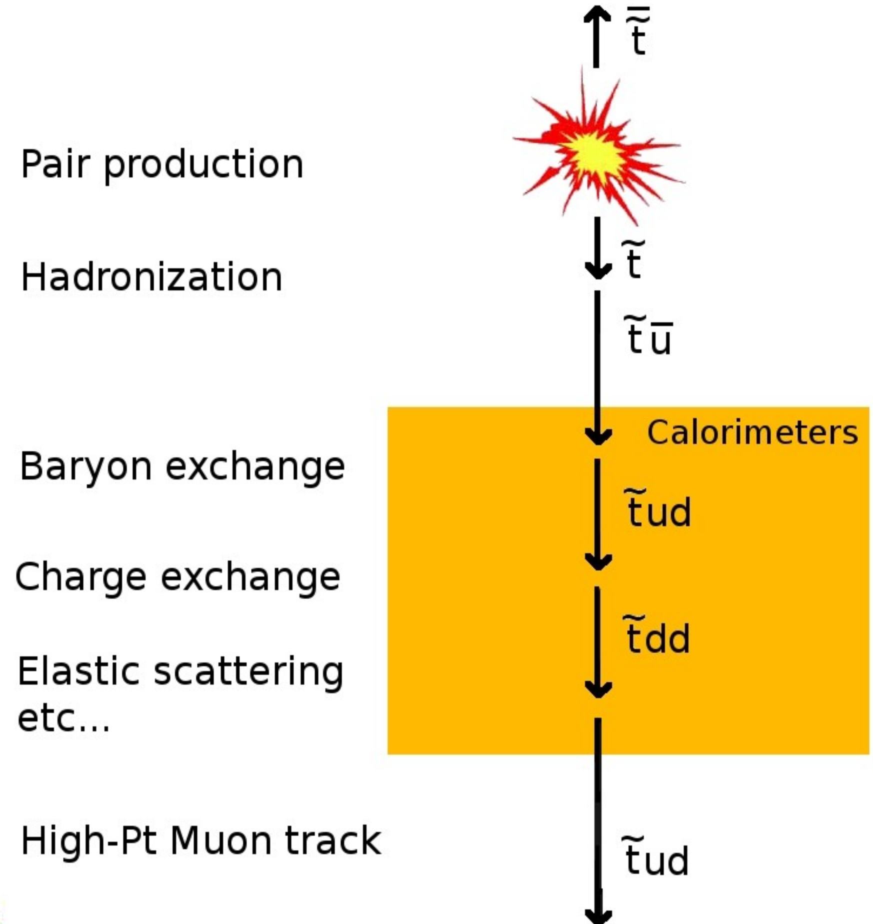
Generic signatures 2^45-1 combinations – Barbier et al.

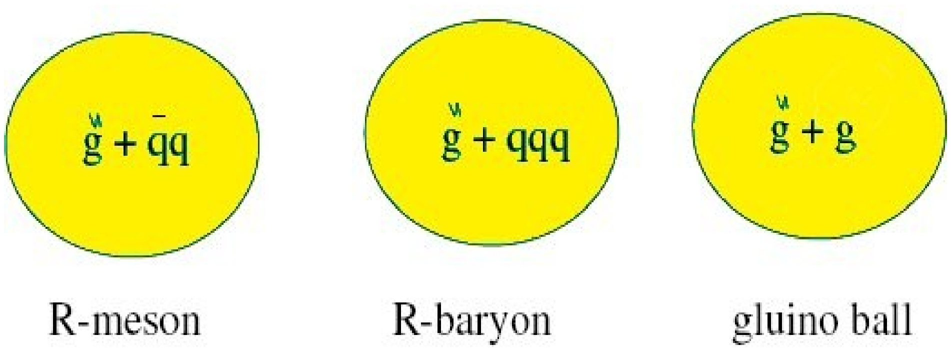
Choose most straightforward decays and signatures

R-hadrons

New particle properties:

- Colored
  (high cross sections at hadron colliders, hadronising)
- *Long-lived* > 50 ns
  (size of detector)
- **Heavy** > 100 GeV

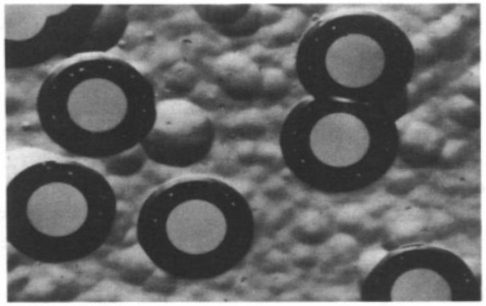




Generic signature:
Penetrating, slow
and high momentum

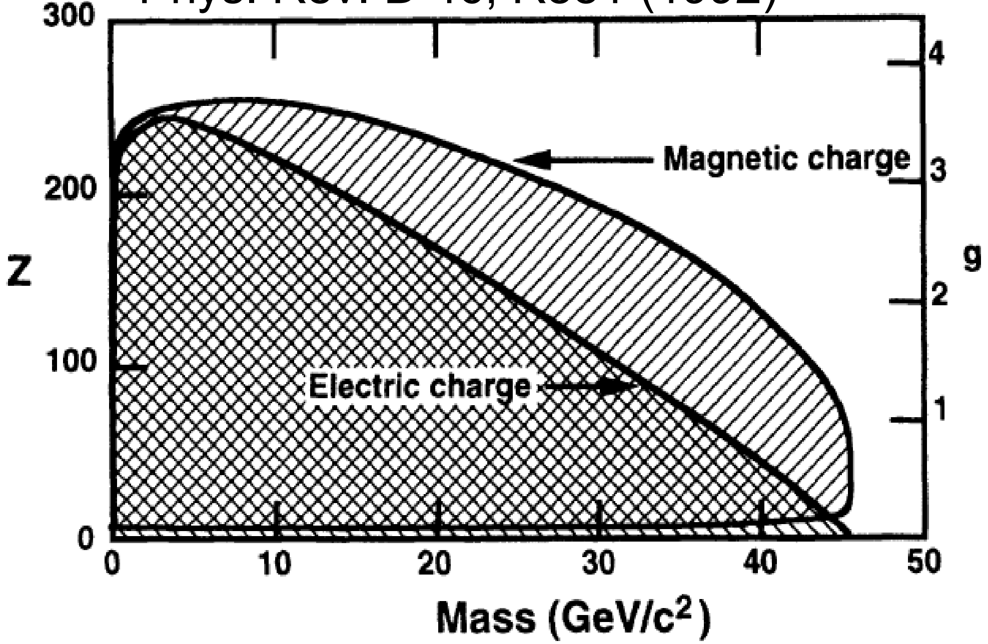
Direct HIP detection: track-etch technique

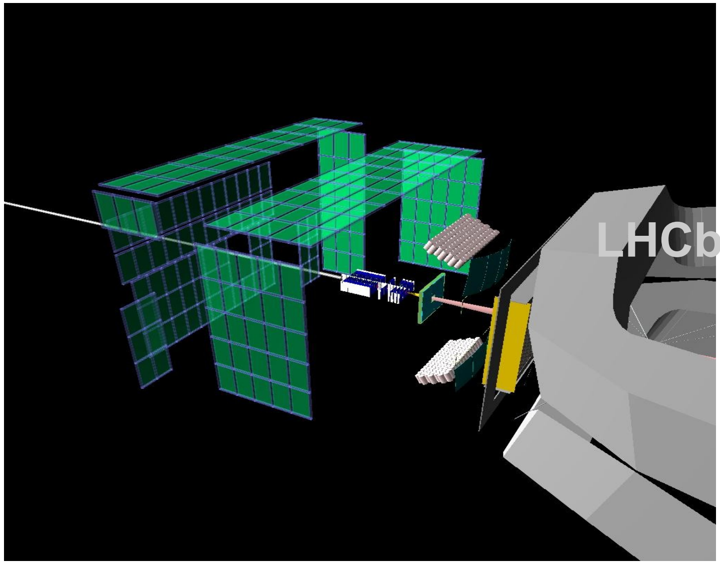
- Pits due to highly-ionizing particles
- Tevatron
- LEP: (MODAL)



- LHC: MOEDAL
  - At Point 8
  - Run in 2014 ?

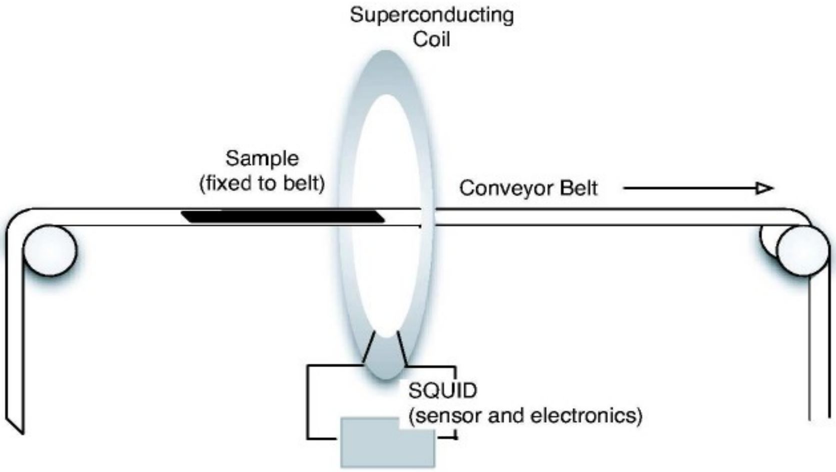
Phys. Rev. D 46, R881 (1992)

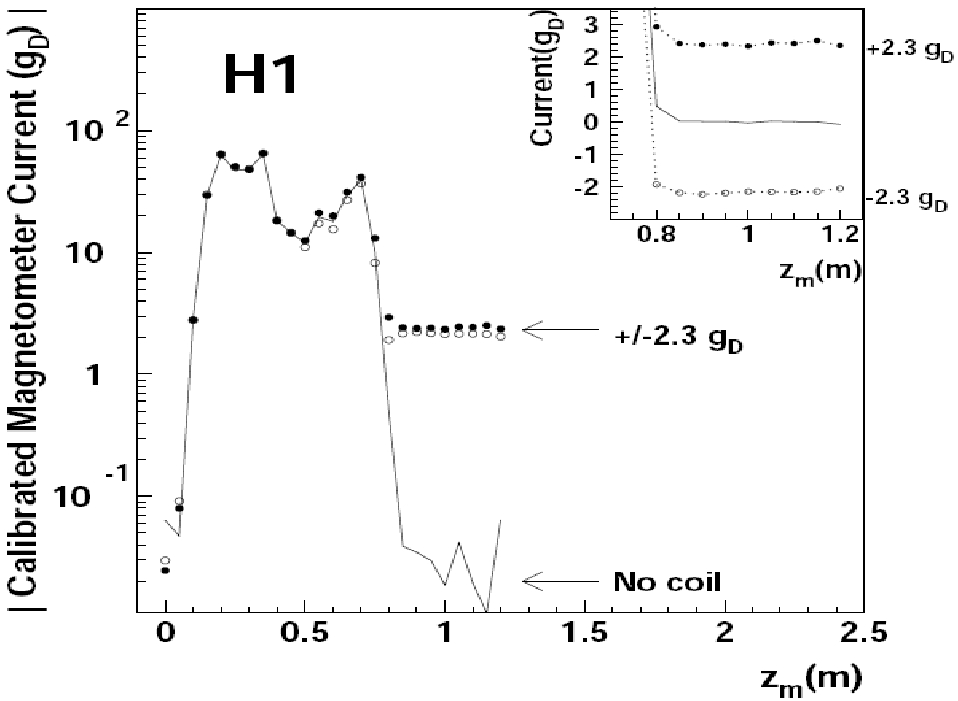




Direct monopole detection: SQUID technique

- At HERA (H1) and the Tevatron (E882)
- Beam pipe and detector material cut into strips
  - Passed through superconducting coil to sense induced current
  - Long solenoid used for calibration
- Trapped Monopoles
  - Model dependence

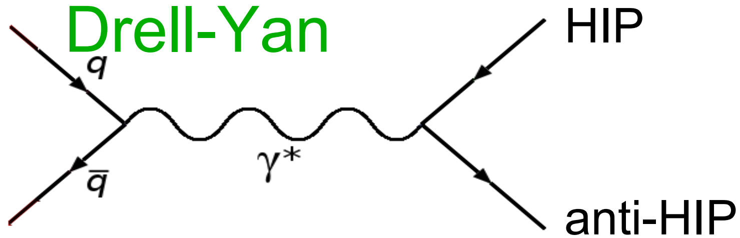




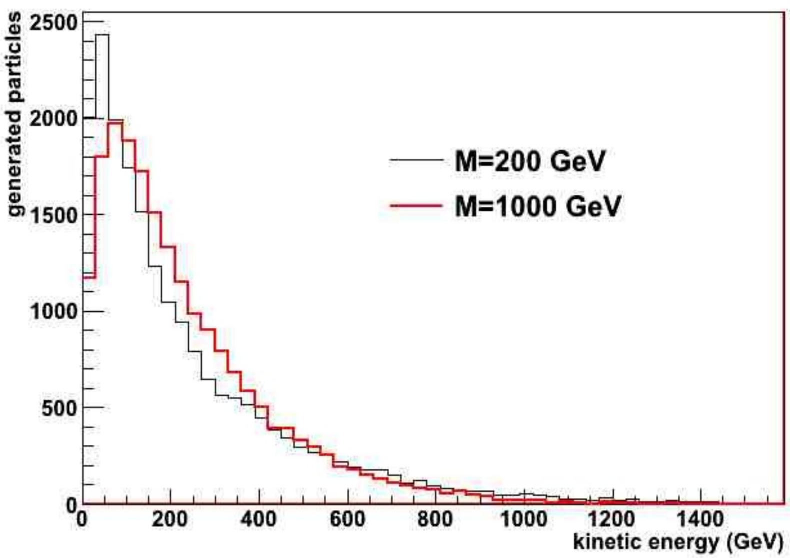
What are the expected HIP energy and angular distributions?

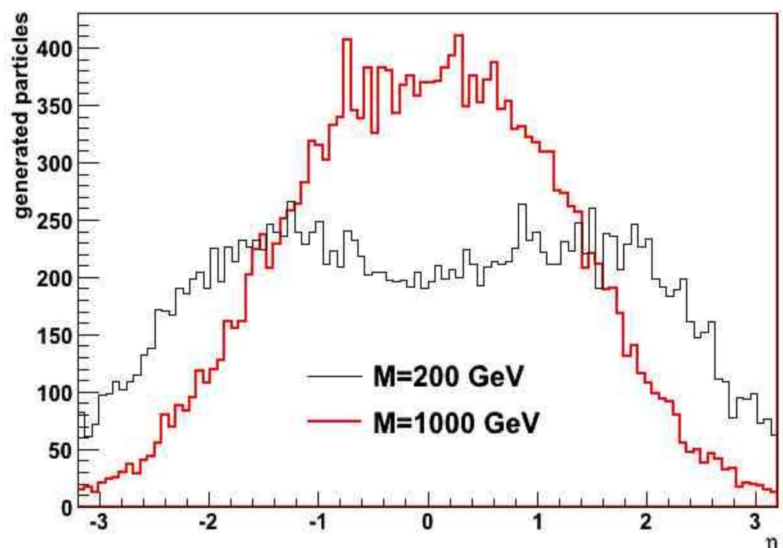
- Strong coupling to the photon prevents perturbative calculations → **cross sections and kinematics cannot be reliably predicted!**
- Putative model of kinematics for typical two-to-two process:

Drell-Yan

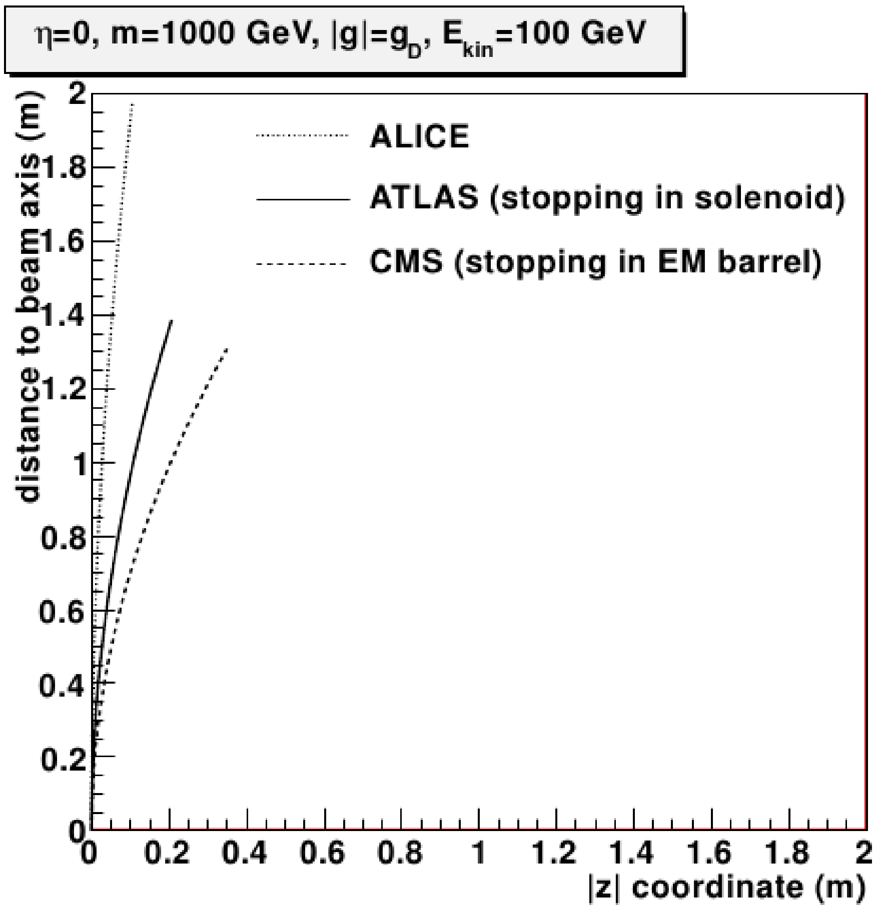


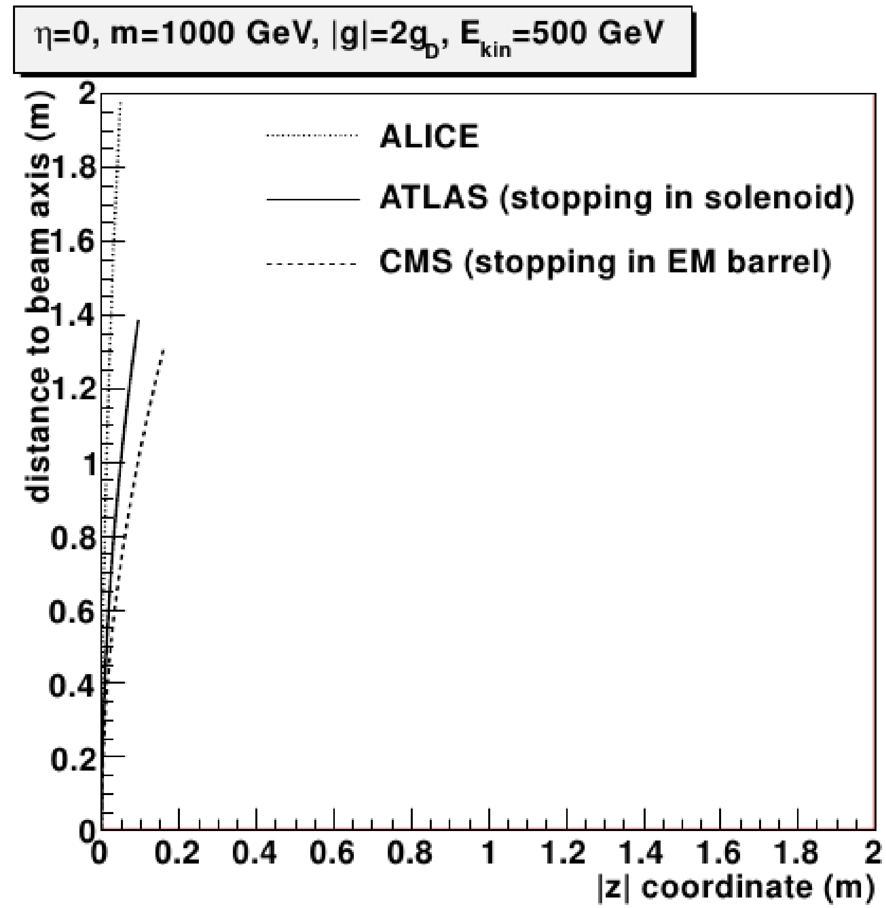
7 TeV *pp* collisions





Monopoles: bending in magnetic field

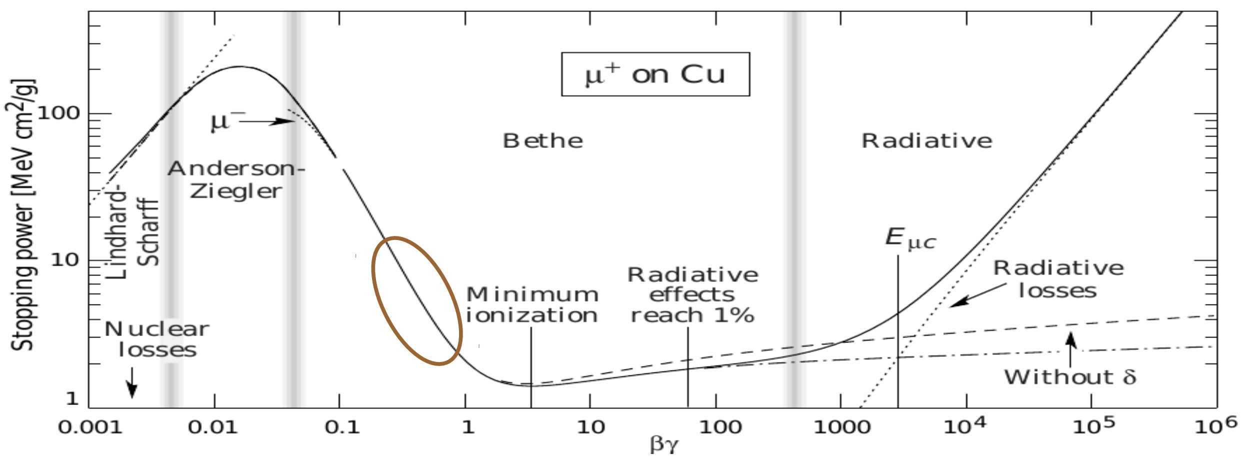




- Acceleration along beam axis
- Straight trajectory in xy plane
- Parabolic trajectory in rz plane

A few comments about "highly ionizing"

- R-hadrons ionize more than muons due to low speed
  - Up to 10 MIPs (β down to 0.4)
  - Generally penetrating through whole detector
- Monopoles/high-charges are very highly ionizing due to low speed *and* high charge (dE/dx α q^2)
  - >> 10 MIPs → highly ionizing particle (HIP)
  - Generally stopping in detector
  - Specific detector effects e.g. saturation, anomalous bending, delta electrons, electron recombination...



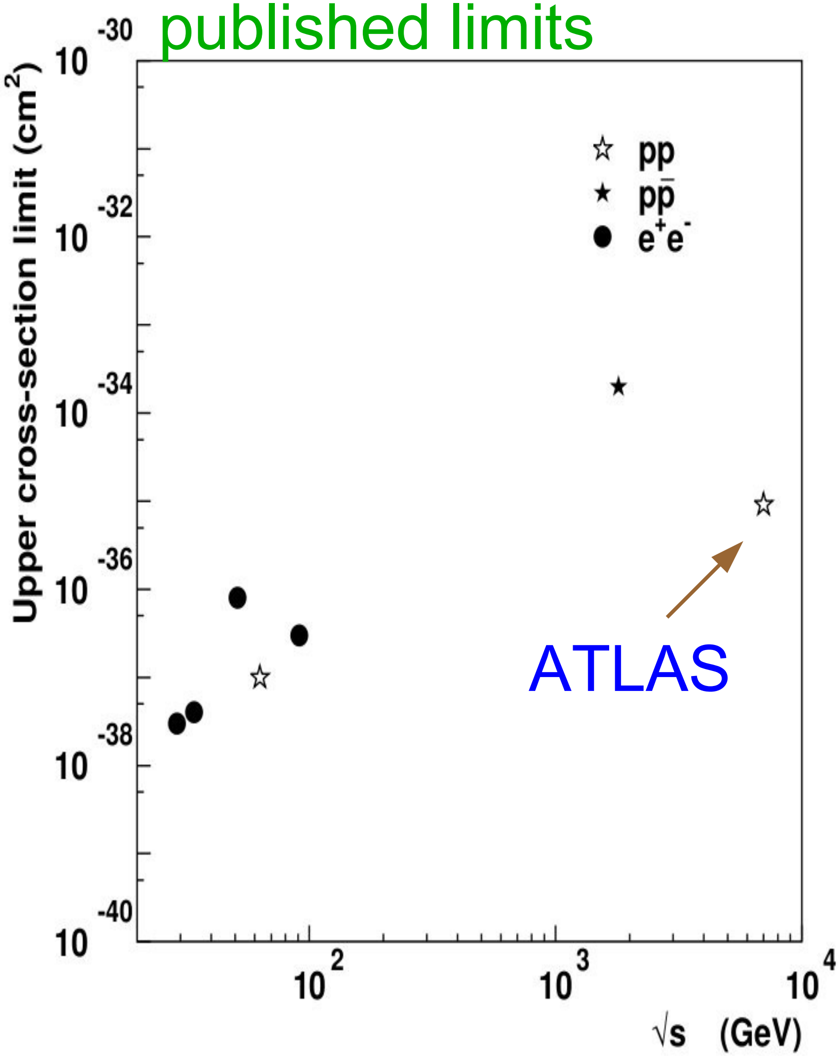
PDG

HIP parameter space: limitations of ATLAS HIP search

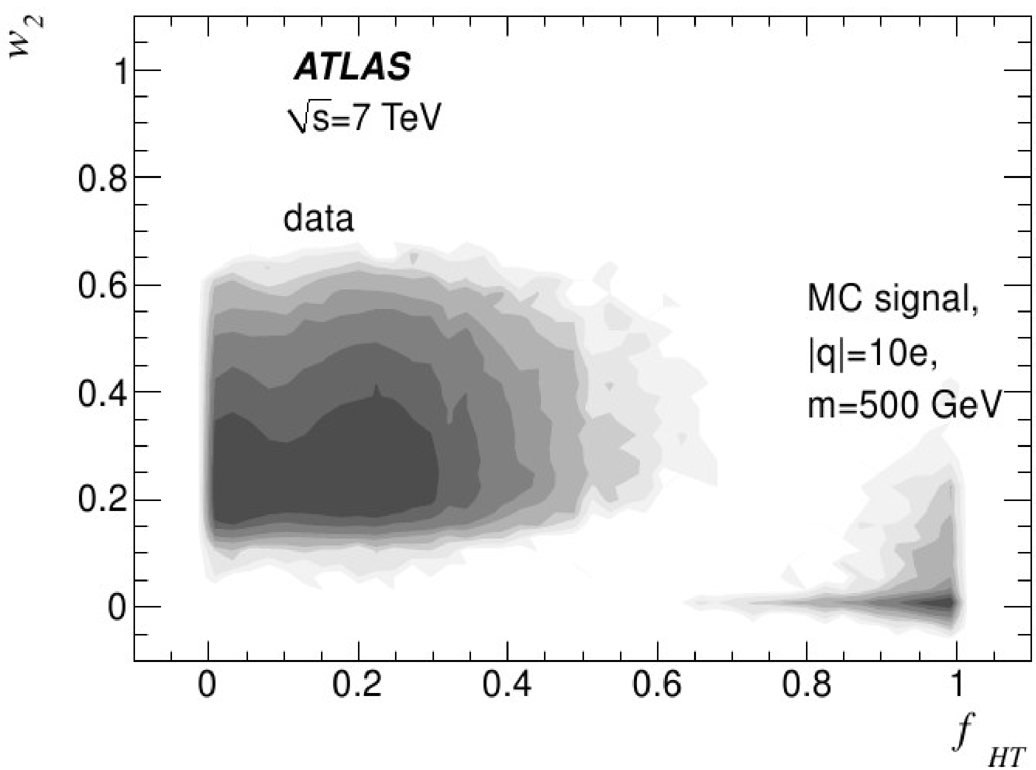
- **|q| ≥ 6e** bound determined by E_T > 10 GeV trigger threshold
  - electron trigger → **HIP must stop in EM Cal**
- **|q| ≤ 17e** bound determined by delta electrons and electron recombination
  - **no interpretation yet for monopoles** for same reasons + bending
- **mass ≤ 1000 GeV** (β ≥ 0.4) bound determined by L1 trigger timing constraints
- **lifetime ≥ 100 ns** to maintain narrow energy deposit

Highly-charged particles

published limits



HIPs: observables and limits



m [GeV]	$\lvert q\rvert = 6e$	$\lvert q\rvert = 10e$	$\lvert q\rvert = 17e$
200	1.4	1.2	2.1
500	1.2	1.2	1.6
1000	2.2	1.2	1.5

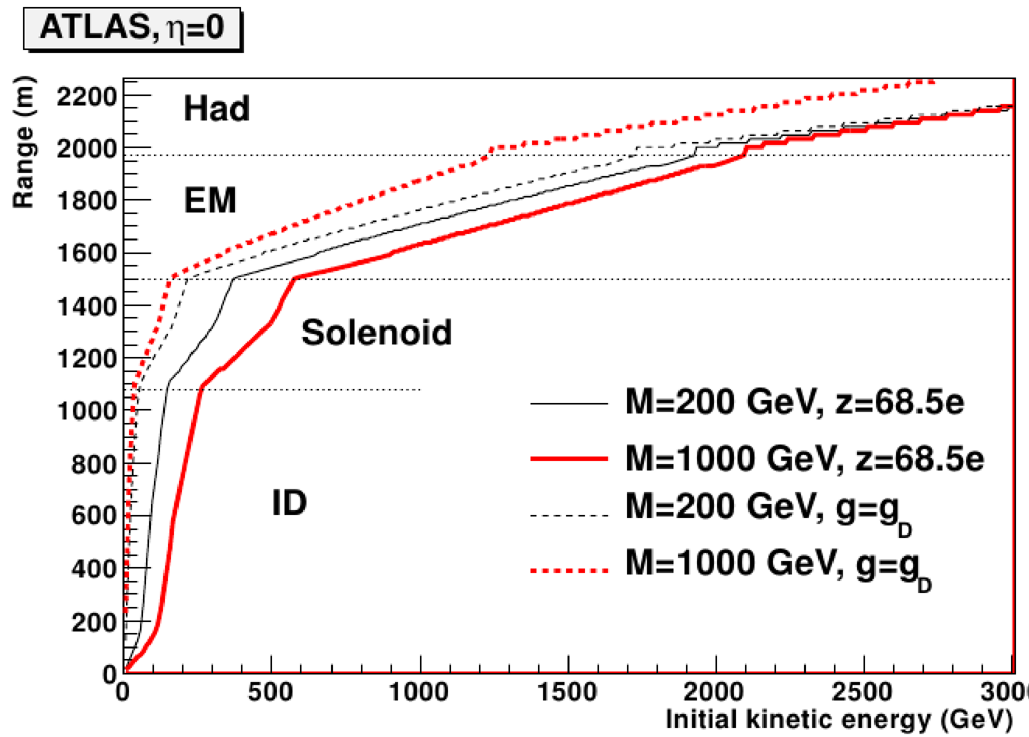
Limits (pb) in kinematic regions of good acceptance

m [GeV]	$\lvert q\rvert = 6e$	$\lvert q\rvert = 10e$	$\lvert q\rvert = 17e$
200	11.5	5.9	9.1
500	7.2	4.3	5.3
1000	9.3	3.4	4.3

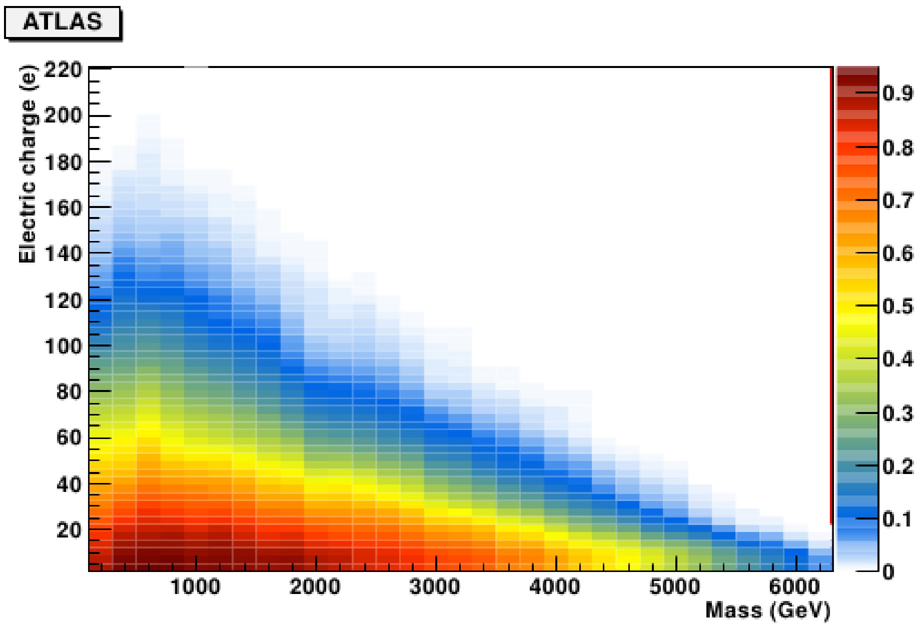
- Limits (pb) for Drell-Yan kinematics

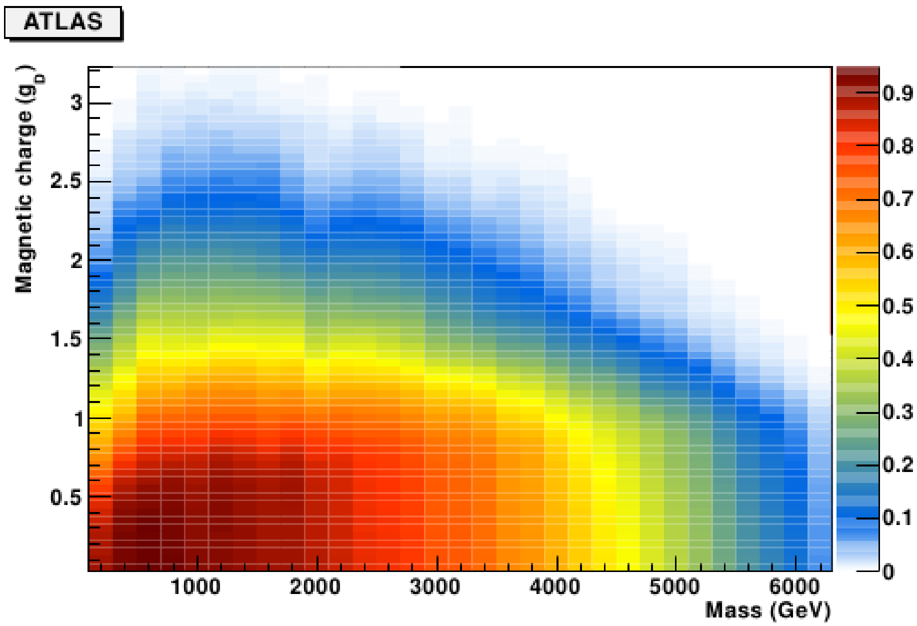
Where do the HIPs stop – mass dependence

Example: range of magnetic monopole and highly charged particle in ATLAS as a function of initial energy
$\rightarrow$ magnetic monopoles of high mass (low speed) punch through more material before stopping

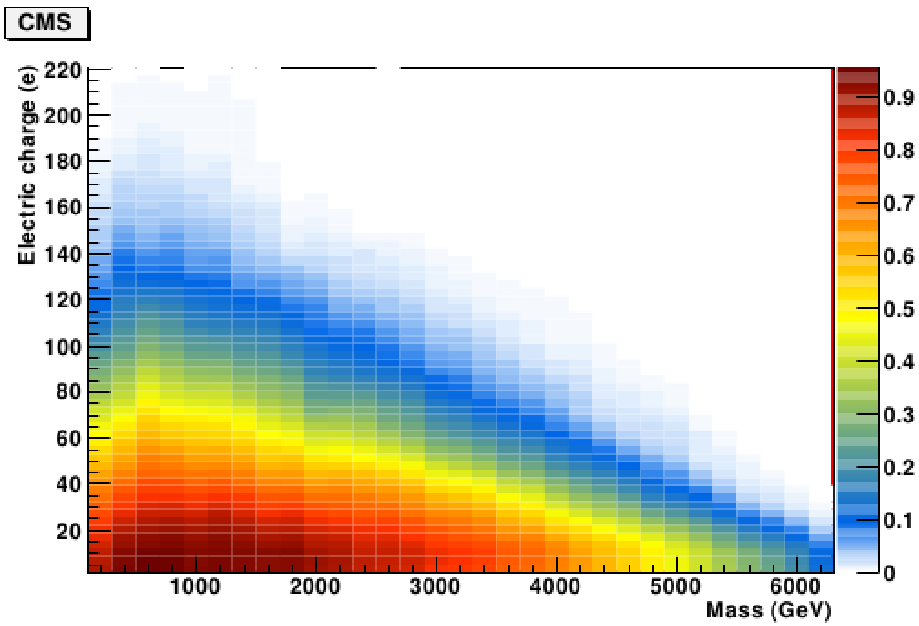


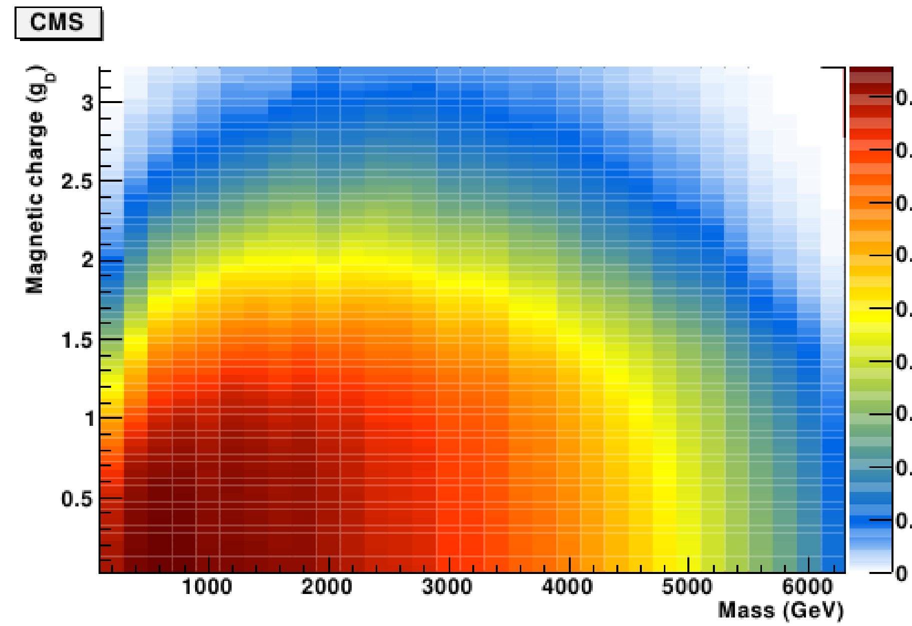
Drell-Yan 14 TeV *pp* collisions



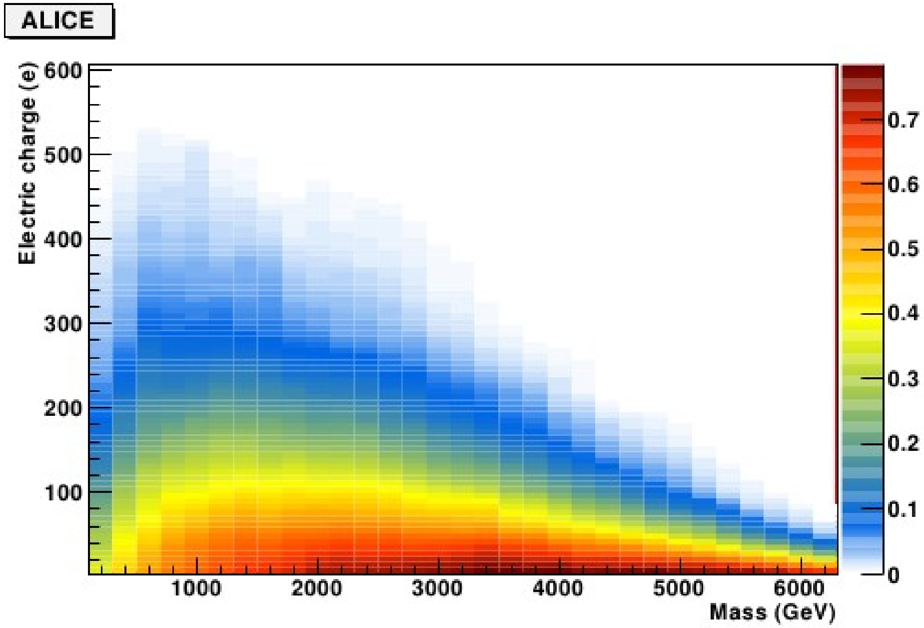


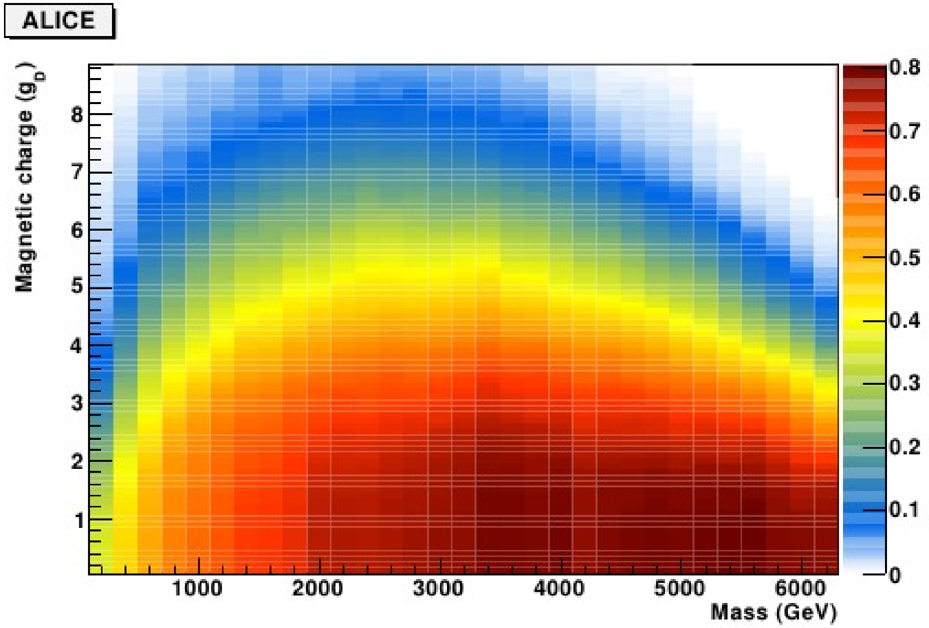
Drell-Yan 14 TeV *pp* collisions



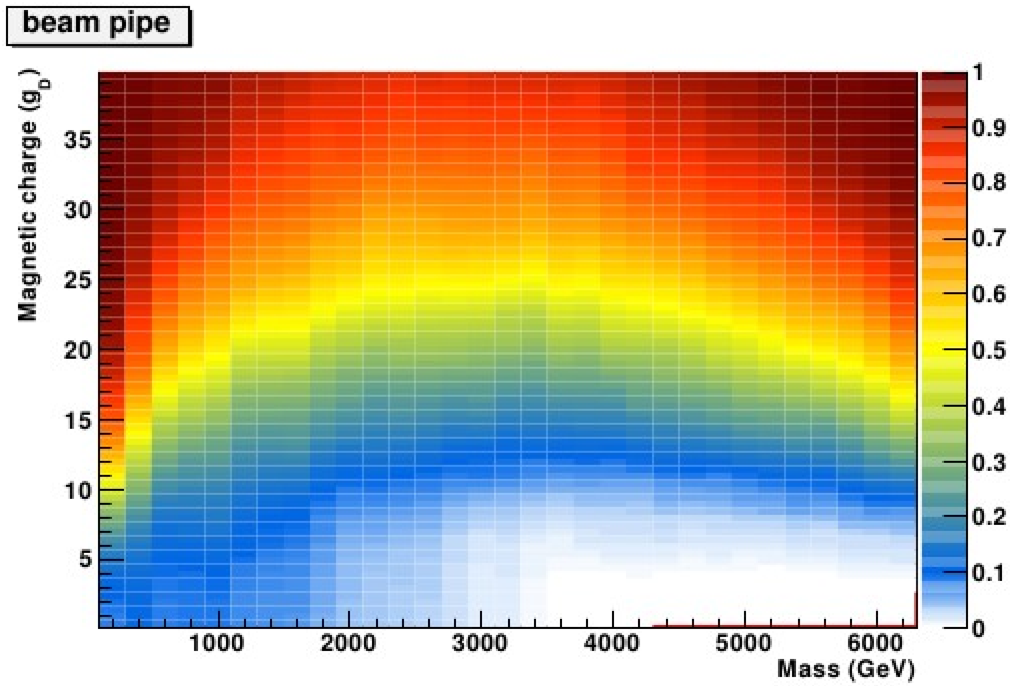


Drell-Yan 14 TeV *pp* collisions





Drell-Yan 14 TeV *pp* collisions



HIP acceptances – systematic uncertainties

- Material budget: 10%
- Approximation in stopping power formula: 10%
- Bending effects: 5%
- **Total: 15%**